Use of Stellar References In Space Navigation

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In this project we used techniques generally grouped as Modern Controls Theory. This theory can be divided into two domains, Control Optimization and Parameter Optimization. Let us defer the second for awhile.

Control Optimization programs an input to make the system "best" by some performance index such as minimum fuel or minimum time. Consider a control law to minimize the time in going from A to B. (Slide I) The practical approach is implemented by a switching curve - which gives us optimum switching (Slide II); note switching occurs at $x + \dot{x} \geq$ const.

In space travel, in an effort to conserve weight, etc., it is desired to minimize fuel. As you know, the fuel to pay-load ratio is about 300-1, so this is surely a worthwhile endeavor. Consideration of the gravity gradients or variations of gravity in interplanetary space permits the calculation of an optimum or minimum fuel trajectory (Slide III). Staying on that trajectory requires midcourse corrections which in turn requires midcourse navigation. (Slide IV)

An error of one minute of arc is approximately one mile in 2000, i.e. S. F. by one mile, but to Mars (e.g. 1 A. U.) a miss of 40,000 miles would result. A sixty times better or one second of arc still causes a 700 mile miss. So mid-course data is needed to determine the corrections required to maintain optimum trajectory. For Apollo and Post-Apollo manned flights, the Theodolite offers the required accuracy of seconds of arc. But realization of this accuracy requires that its base or platform be held stationary with equal accuracy.

Our closest star, Alpha Centauri, is 4.3 l.y. away or 200,000 further than our sun. In transversing a distance equal to the diameter of the earth's path (i.e. two A. U.) Alpha Centauri would appear to change in position by only 3/4 second. So any star offers us a convenience reference for travel in our solar system. Thus, using stellar references obviates gyros with their attendant disadvantages. Now ordinary optics gives us resolution of seconds of arc; we are employing the optical lever arm with a photomultiplier sensor. (Slide V - Schematic of Sensor) Circular scan effects a null for zero-zero aiming. (Slide VI)

Only deterministic signals thus far have been discussed; however, under close observational everything is randon or really Stochastic. By reducing from optical frequencies (of order 10^{14} htz ~ 100,000 Ghtz) to the servo BW (1 htz), the star itself appears deterministic. The culprit in the chain then lies in the sensors, primarily the noise current in the photomultiplier; by fitting laboratory data on the photomultiplier to a Gaussian curve, the minimum error was calculated to be of the order of a second of arc. After in-phase and quadrature demodulation (Slide VII) of the star sensor signals, coordinate transformations gives us the position errors in pitch, roll, and yaw. (Sensors $\pm$ 45° nominally).

We see these errors already have uncertainties of the order of one arc second; the controller then must be parameter optimized so as to minimize the mean squared angular error. Since the system is continuous and the statistics are stationary, we will use the Weiner filter by a Bode-Shannon realization (no poles in right half plane). This filter will be used in the linear mode of the system. The linear mode for small signals has the dampening associated with minimum error and stability. This mode corrects for drift and other small errors. For large errors, e.g. for free use of the theodolite or its accidentally being bumped by the navigator, a nonlinear, maximum effort, or bang-bang mode will achieve optimum (minimum time) control. Note, the nonlinear mode is for optimum control, while the linear mode is for parameter optimization (to minimize error).

Lastly, the correction torques are effected by the interaction of signal currents and the magnetic fields of ceramic magnets (Slide VIII - Schematic of Overall Rig).

The final coordinate transformation required to obtain correction with respect to the space craft coordinates was found impossible, at least without unacceptable approximation of the Euler angles by direction cosines. This difficulty will be circumvented by making the corrections independent of the spacecraft coordinates. This will be effected by interchanging the coils and magnets (i.e. putting the torque coils on the moving frame and the uniform magnets in fixed bearings). (Slide IX) A digital simulation of the signal process showed that the cross-coupling between pitch, roll, and yaw will be less than 25% (Slides X and XI) if the sensor's field of view is limited to 900 square degrees around their nominal aimings of +45, and -45°, respectively. Astronomical references show that there is a second magnitude star in any field of 900 square degrees. As a safety factor and to facilitate acquisition, the sensors are being designed for third magnitude. The small cross-coupling is expected only to cause the systems to null along a rapidly converging spiral.

It is believed that the use of air-bearings instead of gimbals is new. It permits the close proximity desired for maximum torque and application of torque independent of spacecraft coordinates. Also, they have attendant advantages of making the theodolite more accessable to the navigator. (Slide XI - Overall Set-Up) It is pleasing that free space is linear and in turn permits the three light sources to come through the single small spacecraft window without interaction.

Yet to be studied, however, are the errors which will be introduced by refraction through the window; its effect on the sensors do not affect their rigidity but the error will directly affect the navigation data from the theodolite.

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